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13. ABSTRACT *(Maximum 200 words)*

This report summarizes work accomplished under the support of AFOSR Grant No. F49620-92-J-0506 between September 15, 1992 and October 15, 1996. Two independent laboratories at Indiana University contributed to this work, the Hearing and Communication Laboratory in the Department of Speech and Hearing Sciences, directed by C. S. Watson, and the Auditory Research Laboratory in the Department of Psychology, directed by D. E. Robinson. The research includes experiments on the discrimination and identification of a variety of complex sounds including sequences of tones, spectrally shaped waveforms, gaussian noise samples, speech sounds, and familiar environmental sounds. This work has identified and examined several factors that influence the ability to discriminate and identify these kinds of sounds. These factors include stimulus uncertainty, the proportion of the total duration of a sound that is subject to change, the temporal location of a change within a sound, and the details of a sound's spectral-temporal structure. Individual differences in auditory abilities and correlations among these abilities have also been examined, with several studies demonstrating very low correlations between listeners' abilities to hear the details of speech and nonspeech sounds.

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Work Accomplished

A. Tonal Sequences

1. *The proportion-of-the-total-duration (PTD) rule.* Kidd, Watson

We have extended our examination of the role of proportional duration in auditory pattern discrimination to assess the generality of the PTD rule. Earlier work (Kidd & Watson, 1992) has shown that each individual component of an unfamiliar sequence of tones is resolved with an accuracy that increases monotonically with the component's proportion of the total duration of the sequence (the PTD rule). This work was extended to the case of *duration* discrimination. In this case, the dimension affected by changes in PTD (i.e., time) is also the primary dimension of variation within the patterns, as well as the dimension to which listeners must attend to perform the task. Listeners were asked to detect a change in the duration of a single tone in a five-tone pattern using a modified two-alternative forced choice procedure. Target-tone durations were determined by the PTD value (0.1, 0.2, or 0.4) and the total pattern duration (250 msec or 750 msec). Context-tone durations were determined randomly on each trial. A single frequency pattern, consisting of a sequence of ascending frequencies, was used throughout the experiment. The pattern of results obtained after several thousand training trials was essentially the same as that found in the frequency-discrimination experiments. Increases in the proportion of the total pattern duration occupied by the target tone consistently resulted in lower duration-discrimination thresholds.

We have also evaluated a related proposal by Robert Lutfi (1993) which suggests that proportional variance, rather than proportional duration, accounts for the PTD results. Our analysis reveals that the variance-based explanation of the PTD rule cannot account for many findings in the auditory-pattern-perception literature because it relies on a decision variable that preserves little or no information about aspects of pattern structure that influence pattern discriminability. Although variance clearly influences auditory pattern discrimination in many circumstances, the proportional duration of a target tone appears to affect discriminability because of the influence of the temporal structure of a given patten on attentional focussing within that pattern, independent of any effects due to component variability across patterns. (Partially supported by NIH.)

2. *Use of the psychophysical method of adjustment in tonal pattern discrimination.*
Watson, Kidd, Aimee Surprenant, Ward R. Drennan

A difficulty in tonal-pattern research is that several thousand trials are typically required to approach asymptotic discrimination performance under minimal-uncertainty testing conditions. One solution to this problem is to use the method of adjustment to determine thresholds, rather than a forced-choice psychophysical method. In this study the extremely brief times that are required for a listener to achieve perceptual isolation for single components of a multi-tone patterns using the method of adjustment instead of a forced-choice method (minutes as opposed to hours) were demonstrated. A quantitative criterion for ''perceptual isolation'' is reached when a frequency match is made that is as close to the standard as can be achieved when the standard and variable tones are both presented in isolation, rather than in pattern contexts. Not all adjustments are this accurate, however. The most useful distinction between difficult and easy adjustments is shown to be the percent of all the adjustments, for a given combination of target and context tones, that meet this perceptual-isolation criterion. (Partially supported by NIH.)

3. *Properties of the structure of multi-tone sequential patterns that determine the difficulty of perceptually isolating single target components.* Watson, Kidd, Aimee Surprenant, Ward R. Drennan

A method of adjustment was used to establish the importance of each of several structural properties of the context tones, in nine-tone sequences, in determining the perceptual isolability of target components. Successful "perceptual isolation" of a target tone was assumed to be achieved when frequency matches were as accurate as those achieved for tones presented in isolation, generally meaning matching errors of less than 1%--2% for the 50-ms tones in these sequences. The context property that was found to primarily affect the frequency matches was the separation, in Hz, between the target tone and both the local and (to a lesser degree) the remote context tones. Other than its bandwidth, the form of the local pitch contour (the target tone plus the single tones immediately before and after it) had no clear effect on the ability to "hear out" the target tone, i.e., whether the local context was ascending, descending, concave up, or concave down. The contours of the remote context tones (first and last three in the patterns) likewise had no effect on performance. Performance ranged from 25% target tones isolated for the most difficult conditions to 90% for the easiest. (Partially supported by NIH.)

4. *The effects of training method on frequency discrimination for individual components of complex tonal patterns.* Robert F. Port, Catherine L. Rogers, Watson, Kidd

It has been assumed that subjects trained to detect increments in the frequency of all components of complex tonal patterns (broad focus) would be less accurate in detecting changes in a single target tone than subjects who have been trained to detect changes in only that component [e.g., Watson et al., J. Acoust. Soc. Am. 60, 1176--1186 (1976)]. In several experiments, using a number of 750-ms ten-tone patterns, subjects were trained using one of three methods: in the first two, a S/2AFC procedure was used to train subjects to detect frequency increments in a specific target tone (group one) or to detect frequency increments that could occur in any of the ten components (group two), and in the third, subjects were trained only to identify the individual patterns. Subjects trained using these methods were tested on their ability to detect changes in various components of the patterns, including the target tone for the first group. In all of these experiments, only very slight differences in performance were found among the different groups. These results suggest that lengthy experience with a given pattern allows a listener to discriminate small differences in frequency in any of the individual components of that pattern, relatively independent of the nature of that experience. [Additional support from ONR, R. Port Principal Investigator.]

5. *Selective attention to spectral-temporal regions of auditory patterns.* Watson, Li, Kidd, Zheng.

In an extension of the experiment described above, listeners were trained to attend to different spectral-temporal regions of auditory patterns (ten 50-ms tones, 300 - 3 kHz in frequency) under high uncertainty (a different pattern on each trial). One group of listeners was trained to discriminate changes in the early low-frequency region of the patterns, a second group in the late high-frequency regions, and a control group was trained with changes occurring throughout the patterns. Training was conducted for ten sessions, followed by testing at all spectral-temporal positions. Effects of selective training were much more substantial than in the earlier four-pattern experiment. Under the high stimulus-uncertainty conditions, attentional training yields the predicted results: Discrimination is relatively improved for trained, compared to untrained regions. An unexpected result was that the control group's performance was significantly more accurate than that of the group trained to attend to early, low-frequency tones. It is possible that efforts to selectively attend to some spectral-temporal region of an unfamiliar pattern may reduce overall discrimination performance, compared to that achieved when listening for any change in the pattern. (Partially supported by NIH.)

B. Spectrally Complex Sounds

1. *Effects of spectral and temporal uncertainty on the detection of increments in the level of individual tonal components of "profile" stimuli.* Watson, Xiafeng Li.

In a modification of previous profile discrimination experiments (summarized in Profile Analysis, D. M. Green, Oxford University Press, 1988), intensity increments were introduced, in random order, at one of ten temporal positions during the overall duration of eleven-tone profiles, and at one of the eleven frequencies (i.e., a medium level of stimulus uncertainty). The tonal components were equi-log spaced, and five different component ranges were investigated. Differential detectability of the intensity increments over the spectral-temporal ranges of the profiles is remarkably similar to the temporal and spectral distribution of selective attention to individual tonal components of multi-tone patterns (Watson and Li, 1992; Watson, Kelly, and Wroton, 1976). In contrast to the tonal-pattern experiments, when the intensity-increment task was repeated under minimal-uncertainty conditions, performance improved very little compared to that measured under higher uncertainty. It seems likely that the reason is that the large effects of stimulus uncertainty are obtained only when the contextual components as well as the spectral-temporal targets are varied from trial to trial.

2. *Discrimination of static versus dynamic, and log versus harmonic profiles.* C. Watson, W. Drennan.

"Profile" stimuli consisting of multiple simultaneous fixed-frequency sinusoidal components are more representative of naturally occurring sounds than the spectrally simpler waveforms more often used in psychoacoustic experiments. However, most naturally occurring sounds are characterized by dynamic rather than static spectra, and by harmonically spaced rather than the log-spaced components used in most profile experiments. In preparing to study a variety of dynamic profiles, the discriminability of static and frequency-glide profiles was determined, using both log- and harmonically spaced components. Discriminations were based on the detection of an intensity increment added to the mid-frequency component of 11-component, 400-ms profiles. Each profile had a starting frequency range of 200 to 2000 Hz. Dynamic profiles increased in frequency continuously over their 400-ms durations. Each subject was run under four stimulus conditions (static-log, static-harmonic, dynamic-log, dynamic-harmonic) for a minimum of 2000 trials per condition, in an adaptive-tracking procedure. Mean differences between asymptotic thresholds for the stimulus conditions were small compared to differences among the subjects. Harmonic spacing yielded somewhat lower thresholds than did the log-spaced components, while very modest differences, if any, were found between static and dynamic profiles.

Because of the variability across subjects in this experiment, a group of forty-six new subjects were selected and tested for 1920 trials on a static-log profile. The distribution of thresholds for these subjects was skewed to the right slightly but was roughly normal with a range of -2 to -26 dB (signal level re component level). No evidence was found to suggest that profile-discrimination ability is bimodally distributed, as some have suggested. A group of subjects was selected from each tail of the distribution and tested again using the four profiles (static-log, static-harmonic, dynamic-log, dynamic-harmonic). For these listeners, static profiles yielded slightly better performance than the frequency-glide profiles, regardless of subject ability.

3. *Determinants of the perceptual similarity of complex filter shapes.* C. Watson, and Y. Zheng.

Sounds were created by passing an increasing-frequency 300-ms sawtooth (120--170 Hz) through each of the 15 complex filters. The filters were created by varying two parameters of a pair of overlapping second-order filters (CF: 500 and 1500 Hz). The parameters varied were the width of the upper filter (Q: 1, 3, 8) and the relative amplitudes of the two filter peaks (+12, +6, 0, -6, or -12 dB).

Listeners judged the similarity of pairs of these sounds, equated for energy, using a ten-point scale. A multidimensional scaling (MDS) analysis suggested that when Q of the upper filter was low, the sounds were distinguished entirely on the basis of the relative amplitudes of the filters. For high upper-filter Q values, a different intensity-related dimension was the basis for distinguishing among the sounds, which were essentially identical on dimension No. 1. The two dimensions are associated with overall pitch, and with the salience of the high-frequency spectral peak. Various physical models have been fitted to the data. (Partially supported by NIH.)

C. Individual Differences

1. Individual differences in speech and nonspeech processing among normal-hearing subjects. C. Watson, A. Surprenant.

Although a large portion of the variance among listeners in auditory speech processing is associated with the audibility of components of the speech waveform, it is not possible to predict individual differences in speech perception strictly from the audiogram. Psychoacoustic measures of spectral-temporal acuity with nonspeech stimuli also have been shown to correlate only weakly (or not at all) with speech processing. In a replication and extension of an earlier study (Watson et al., J. Acoust. Soc. Am. Suppl. 1 71, S73) 100 normal-hearing college students were tested on speech perception tasks (nonsense syllables, words, sentences in a noise background) and on 6 spectral-temporal discrimination tasks using simple and complex nonspeech sounds. Factor analysis showed that the abilities that explain performance on the nonspeech tasks are quite distinct from those that account for performance on the four speech tasks. Performance was significantly correlated among speech tasks, and among nonspeech tasks. Either, (a) auditory spectral-temporal acuity for nonspeech sounds is orthogonal to speech processing abilities, OR (b) we have yet to identify the appropriate task or types of nonspeech stimuli that exercise the abilities required for speech recognition.

1. TBAC II. A new version of the Test of Basic Auditory Capabilities. C. Watson, G. Kidd, B. Gygi.

Several psychoacoustic tests have been prepared and evaluated for a new version of the TBAC, a test battery originally developed by Watson et al. (1982). The goal of the new set of tests is to examine abilities that may not have been adequately tested in the earlier versions of the test. Some evidence suggests that listeners may employ more holistic listening strategies when presented with spectrally complex sounds that change over time. Such sounds have more in common with speech and many familiar nonspeech sounds than do the simpler sounds and tonal sequences included in the current TBAC.

The following tests have been added to the new TBAC. All tests follow the same general procedures as used with the current version of the TBAC. The first four tests employ a modified two-alternative forced choice paradigm (S/2AFC), and the familiar-sound identification test utilizes a three-alternative forced-choice identification paradigm.

1. <u>Detection of amplitude change over frequency</u>: Measures threshold ripple depth for subjects to discriminate between rippled noise and flat-spectrum noise.

2. <u>Detection of amplitude change over time</u>: (Temporal modulation transfer function.) Measures modulation detection thresholds at various carrier frequencies.

3. <u>Gap detection</u>: Measures threshold duration for detection of a gap in noise.

4. <u>Gap discrimination</u>: Measures threshold gap-duration difference for detection of a difference in gap durations in successive bursts of noise.

5. Identification of familiar sounds in noise: Measures threshold signal-to-noise ratios for the identification of familiar sounds in noise. Thirty common sounds were taken from a high-quality digital sound-effects library. All sounds were quite recognizable in the absence of noise.

The range of performance on these new tasks is quite consistent with the older TBAC tests. Preliminary analyses indicate that tests 1, 3, and 4 are highly correlated with most of the older nonspeech TBAC tests, while tests 2 and 5 appear to be somewhat less so. None of the new tests is significantly correlated with the speech tests. (Partially supported by NIH.)

2. Identification of familiar sounds. C. Watson, G. Kidd, B. Gygi.

Most studies of auditory recognition and identification have employed either speech stimuli or nonspeech sounds generated in the laboratory (e.g., tones of various frequencies, tonal patterns, click trains). The present study employed 25 naturally occurring complex sounds (obtained from a commercial sound-effects library), such as those produced by doors closing, babies crying, helicopters in flight, and other familiar events. These sounds, equated for peak levels, were recorded with a background of broad-band noise. The recorded sounds were presented to groups of 6 to 8 listeners in both open-set and closed-set formats (with the list of responses displayed continuously in the latter). Confusion matrices were generated using a wide range of event-to-noise (Ev/N) ratios. Two frequent confusions were identified for each item, and were used to create a three-alternative forced-choice test. Eight values of Ev/N were selected for each item in an effort to achieve uniform item identifiability.

We have found a wide range of variation in identification thresholds and in the steepness of the psychometric functions obtained with the familiar sounds. The lowest thresholds were obtained with sounds that have a well-defined temporal pattern. It appears that the temporal pattern can specify a sound source with a relatively small amount of spectral information available. Confusions also indicated that listeners tend to rely on temporal characteristics at the lower S/N ratios. The steepest functions were obtained with sounds that had the most uniform sustained levels. For these sounds, most of the information required for identification became audible within a small range of S/N ratios, and identification performance went from chance to near perfect with very small increases in the S/N ratio. Individual differences were somewhat smaller than found with speech perception. The difference between average thresholds for the poorest performing decile and the best-performing decile was approximately 4 dB, as compared to roughly 7 dB for speech. Although our findings are likely to have been affected by the size and makeup of the particular set of sounds we have utilized, the tendencies in the data described here appear to be ones that have considerable generality. (Partially supported by NIH.)

3. Auditory and Visual Speech Perception: Confirmation of a Modality-Independent Source of Individual Differences. Watson, W. Qui, M. Chamberlain, S. Li.

Two experiments were run to determine whether individual differences in auditory speech recognition abilities are predictable from those for speechreading (lipreading), using a total of 90 normal-hearing college-student subjects. Tests included single words and sentences, recorded on a video disk by a male actor (Johns Hopkins Lipreading Corpus, Bernstein and Demorest, 1986). The auditory speech was presented with a white noise masker, at -7 dB Sp/N. The correlations between overall auditory and visual performance were 0.52 and 0.43 in the two experiments, suggesting the existence of a modality-independent ability to perceive linguistic "wholes" on the basis of linguistic fragments. Subjects in the second experiment also identified printed sentences, with 40-60% portions of the printed characters deleted. Performance on this "Fragmented-Sentences Test" also correlated significantly with auditory and visual speech recognition. The existence of a modality-independent source of variance in speech recognition abilities may be a partial explanation of the

difficulty in demonstrating strong associations between psychoacoustic measures of spectral or temporal acuity, and speech discrimination or identification.

D. Noise Discrimination

1. Discriminability of noise samples. M. Rickert, D. Robinson.

In previously reported work [S. F. Coble and D. E. Robinson, *J. Acoust. Soc. Am. 92*, 2630-2635 (1992); M. E. Rickert and D. E. Robinson, *J. Acoust. Soc. Am. 93*, 2386(A) (1993)] listeners discriminated among trials consisting of either two identical samples of noise or two nonidentical samples. Nonidentical samples were generated by replacing a segment of noise presented during the first interval with a new segment. Although the long-term power spectrum of the segments was the same, the temporal position at which segments were replaced had a significant effect on discriminability: Performance was best when changes occurred at the end and was poorest when changes occurred at the beginning. In the present study, the effects of temporal position were measured under two spectral conditions. In one condition, noise samples were identically filtered (100-3000 Hz or 455-655 Hz) for the entire stimulus duration (50 ms). The effect of temporal position is reduced with narrow-band stimuli but is not eliminated. In a second condition, the bandwidth was varied within each sample such that one segment was wideband (100-3000 Hz) and the other narrow band (455-655 Hz). Overall performance with mixed stimuli (1) is similar to that with pure wideband noise when the uncorrelated segment is wideband, and (2) is similar to that with pure narrow-band noise when the uncorrelated segment is narrow band.

In the noise-discrimination experiments described above, center frequency was held constant at 545 Hz. An additional experiment has been conducted in which both center frequency (545 Hz and 2000 Hz) and bandwidth (200 Hz and 1000 Hz) were varied. Data were also obtained with wideband (100 Hz) noise. Although the effect of temporal position was consistent across stimulus conditions, the size of the effect was reduced for narrower bandwidths. There was no evidence of an effect of center frequency.

2. Leaky integrator models. D. Robinson, M. Rickert.

Two models have been developed that describe the results of our noise-discrimination experiments. In each model the waveforms from the two temporal intervals are jittered in amplitude, filtered, and squared or rectified. In one model, the resulting waveforms are passed through a leaky integrator and subtracted from one another. This difference waveform is squared and passed through a second leaky integrator. A sample of the output of the second-stage leaky integrator taken at the end of the integration period is used as a decision variable from which hit and false alarm rates are obtained and d' is computed. In the other model, the squared waveforms are multiplied by an exponential weighting function before subtraction. A signal-to-noise statistic is then used to obtain an estimate of d'. The fitting parameters for each model are the variance of the internal noise process and the time constant of either the second-stage integrator or of the exponential weighting function. The models provide an excellent fit to the data reported by Coble and Robinson. They provide quantitative predictions of the improvement in performance as the target (uncorrelated) noise segment is moved from the beginning to the end of the burst and they predict the constant ratio of the duration of the target segment to the total duration.

E. Speech Perception

1. Formant Frequency Discrimination. Kewley-Port and C. Watson.

Discrimination thresholds for formant-frequency discrimination, for F1 and F2, were obtained for ten synthetic English vowels (Kewley-Port, 1990; Kewley-Port and Watson, 1993). In general, thresholds values of ΔF as a function of formant frequency are best described as a piecewise-linear function which is constant at 14 Hz in the F1 frequency region (<800 Hz), and increases linearly in the F2 region. In the F2 region, the resolution for formant frequency is about 1.5%. Minimal-uncertainty thresholds are similar to the most accurate discrimination previously reported in the F1 region, but about a factor of three lower (more precise) in the F2 region. Thresholds were also measured for one vowel, /I/, in a variety of consonantal contexts, /b, d, g, z, m, l/ (Kewley-Port and Watson, 1991). For F1 and F2, the resulting thresholds were a factor of about 4-5 smaller than those reported by Mermelstein (1978). Additional experiments estimated formant frequency thresholds under medium stimulus uncertainty (Kewley-Port, 1992). While training required longer to approach asymptote, and levels of performance were higher for some CVC's than for others, final thresholds were generally similar to those obtained for isolated vowels. Apparently, auditory acuity for formant frequency discrimination for well-trained subjects is generally the same for vowels in isolation and in CVC contexts, under both minimal and medium levels of stimulus uncertainty.

The results of these experiments also suggested a trend for higher fundamental frequency to produce increased formant thresholds for these synthetic female vowels. Further studies investigated the effect of glottal source on formant thresholds in synthesized male vowels. Thresholds for formant-frequency discrimination were obtained for six vowels with two fundamental frequencies: high (126 Hz) and low (101 Hz). Four well-trained subjects performed an adaptive tracking task under minimal-uncertainty conditions. Discrimination thresholds for vowels with high F0 were significantly greater than those with low F0. Consistent with results for female vowels, thresholds for frequencies below 800 Hz in the F1 region appeared relatively constant while thresholds in the F2 region were increasing. There was a general trend across all male and female vowels for higher fundamental frequency to result in increased discrimination thresholds. (Partially supported by NIH.)

2. The effect of discriminability on dimensional interactions of pitch with vowel and consonant identity. Surprenant, Kewley-Port and Watson.

The ability to ignore irrelevant variation in the speech signal is essential for normalizing across speakers and situations. Past research has indicated that irrelevant variation in such features as pitch and vowel quality caused more interference on a consonant classification task than the reverse. Along with other more memory-oriented paradigms such as serial-list recall, this has been taken as evidence that the longer-lasting, periodic elements of sound that make up vowel and pitch information remain longer in auditory memory, thereby interfering with judgments about consonant identity. However, in most of these demonstrations, the relative discriminability of the tokens was not controlled. In the present study, discriminability was assessed for continua of pitch, consonant, and vowel identity for stop-vowel syllables. Eight well-trained subjects were asked to make speeded same-different judgments on one dimension of stimuli that varied on two dimensions. An interaction for both response time and accuracy was found such that as the discriminability of the relevant dimension was increased, interference from the irrelevant dimension decreased and vice versa. Although there were minor variations, the same general pattern was observed in all conditions. (Partially supported by NIH.)

F. Methodology

1. Robustness of psychophysical measures. Rickert, Robinson.

A mathematical analysis of several well-known measures of psychophysical performance has been completed. In this work we were interested in the degree to which such measures as d', P(C), P(C)max, and A' are "robust" with respect to violations in their underlying assumptions. The basic approach was to investigate how each of these measures varies with changes in criterion placement for various pairs of assumed underlying density functions. The pairs of density functions investigated were normal-normal, exponential-exponential, Chi Square-Noncentral Chi Square, and Rayleigh-Rice.

Our findings indicate that measures which rely on the assumption of equal-variance, normal densities, such as d' and P(C)max, are quite robust, particularly if extreme values of the criterion are avoided, e.g. changes in the criterion have small effects except for very low or very high false alarm rates. The so-called non-parametric measure, A', is not robust, and, in fact, shows large changes in magnitude as the criterion is varied on any of the density pairs we investigated.

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